A SIMPLE MODEL FOR DESCRIBING RADON MIGRATION AND ENTRY INTO HOUSES *(Wed., First Group, 9:05 a.m.)*

R. B. Mosley

U.S. Environmental Protection Agency, Research Triangle Park, North Carolina

While it is quite possible to formulate a fairly rigorous mathematical model to describe radon transport through soil, such a model would require rather complex numerical solutions that would be time consuming and expensive to evaluate. Numerical solutions are also cumbersome for evaluating the relative importance of individual mechanisms and for evaluating the appropriateness of alternative boundary conditions. Analytical solutions, even if only approximate, are much more informative for understanding the relative importance of specific physical mechanisms.

A simplified model for soil-gas transport through soil surrounding the substructure of a house will be discussed. This model will attempt to answer, in semi-quantitative terms, such fundamental questions as: (1) What role does diffusion play in transporting radon to the house-soil interface, where pressure-driven flow tends to dominate the process of entry into the house? (2) Do active subslab depressurization mitigation systems significantly increase the rate of emission of radon into the ambient air? (3) At what flow rate through the subslab depressurization system does dilution of the radon in the soil gas contribute significantly to the performance of the mitigation system?

Simplifying assumptions about the distribution of entry routes and driving forces will be used to relate indoor radon levels to soil characteristics and to the dynamics within the house. Preliminary validation of the model predictions will be provided, using data from selected research houses.

DESIGN AND PERFORMANCE OF A RECIRCULATING RADON-PROGENY AEROSOL GENERATION AND ANIMAL INHALATION EXPOSURE SYSTEM* *(Wed., Second Group, 3:30 p.m.)*

G. J. Newton, R. G. Cuddihy, H. C. Yeh, and B. B. Boecker

Inhalation Toxicology Research Institute, Albuquerque, New Mexico

It is not possible to measure the exact alpha dose that each airway cell type receives from inhalation to radon progeny, therefore we have developed methods for estimating dose by biodosimetry. This approach compares an *in vitro* response from exposure to measurable alpha-particle doses with similar responses observed *in vitro* following inhalation exposure to radon progeny.

Because the calibrated *in vitro* exposures must be completed before cell division occurs, the corresponding inhalation exposures must also be completed in as short a time as possible. Inhalation studies using laboratory animals exposed to ^{222}Rn progeny attached to vector aerosols that are typical of indoor and mine environments are being conducted at the Inhalation Toxicology Research Institute. These studies require exposures of up to 1000 working level months (WLM) within a few hours. Thus, large amounts of ^{226}Ra are needed to produce the gaseous ^{222}Rn.

A once-through exposure system was considered impractical because of statutory discharge limitations for radon and the large amounts of radium that would be required. Therefore, we designed and constructed a recirculating exposure system that removes the aerosol after it has passed through the exposure chambers and recirculates the remaining purified radon. The purified radon and air mixture is passed into a reaction aging chamber, where attachment of radon progeny to the vector occurs. Design criteria include:

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(1) 45 mg of ^{226}Ra in a radon generator, (2) 40 L/min total flow rate, (3) CO_2 removal, (4) reconstitution of oxygen tension and water vapor content to atmospheric levels, and (5) a trap for capturing radon gas. Radon-progeny exposure concentrations in the range of 5,000 to 100,000 WL have been produced.

The experimental design, aerosol generation system, the animal inhalation exposure system, and methods used to characterize the high-level exposure atmospheres will be discussed.

RADON TRANSPORT PROPERTIES OF SOIL CLASSES FOR ESTIMATING INDOOR RADON ENTRY

(Wed., First Group, 9:30 a.m.)

K. K. Nielson and V. C. Rogers

Rogers and Associates Engineering Corp., Salt Lake City, Utah

Radon diffusion coefficients and air permeabilities of soils are required for modeling indoor radon entry, for interpreting data on soil radon sources, and for designing and evaluating potential radon mitigation or containment systems. Diffusion and permeability coefficients depend on soil moistures, particle sizes, and compactions. We present a systematic method for estimating these transport parameters for the 12 common Soil Conservation Service (SCS) soil particle-size classes for predicting radon entry.

Diffusion coefficients and air permeabilities are estimated from predictive correlations with soil particle-size (grain) distribution, porosity, and water matric potential. The matric potential and grain sizes are preferred for estimating soil moistures when site-specific data are unavailable because long-term average matric potentials near structures are relatively constant. They provide a useful basis to compare radon transport properties of different soil types in a given location.

Predicted diffusion coefficients range from about 10^{-9} m^2 s^{-1} for the silty clay class to 4×10^{-6} m^2 s^{-1} for the sand class. Air permeabilities range from 8×10^{-18} m^2 for the silty clay class to 2×10^{-11} m^2 for the sand class. Comparison of measured diffusion and permeability coefficients with predicted values are within geometric standard deviations of 1.4 and 1.7, respectively.

The method provides generic diffusion and permeability coefficients as functions of soil type and matric potential. Because long-term average matric potentials near structures are relatively constant (10 to 30 kPa), specifying the soil type characterizes the soil radon transport properties sufficiently for estimating indoor radon entry.

TECHNICAL AND PUBLIC POLICY CONSIDERATIONS IN THE DEVELOPMENT OF A CODE FOR THE CONTROL OF RADON IN RESIDENCES *(Wed., First Group, 4:25 p.m.)*

M. Nuess and S. Price

Washington State Energy Office, Spokane, Washington

Building codes that address radon control in residential buildings are a relatively new development in the larger trend toward increased efforts to understand and control indoor air quality. A residential radon construction standard has been developed in the Pacific Northwest region of the United States. The Northwest Residential Radon Standard (NRRS) seeks to provide a measured public policy response that is commensurate with current knowledge of both the health risk and the state of building science. This paper reviews the range of potential public policy responses available to deal with radon as a public health problem, describes the policy framework on which the NRRS is structured, and explains the development process.

As an external pollutant source, radon is dependent on certain aspects of building science for control. Pressure-driven flow of soil air is the key transport process addressed by this code.

Time and budget constraints limit the scope of the NRRS to identifying minimal measures necessary to reliably achieve radon reductions without impairing structural integrity, capability to control other indoor air pollutants, occupant comfort, or energy efficiency. The NRRS favors measures that enhance the linkages among durability, indoor air quality, and comfort. However, the standard does not require them unless they are part of the minimal requirements necessary for radon control. The NRRS, then, serves to provide a useful interim step toward the larger goal of a systematic approach.

RADON TRANSPORT FROM THE SUBSURFACE: THE ROLES OF CERTAIN BOUNDARY CONDITIONS AT SUBSURFACE/ENVIRONMENT BOUNDARIES* *(Wed., First Group, 11:05 a.m.)*

P. C. Owczarski, D. J. Holford, H. D. Freeman, and G. W. Gee

Pacific Northwest Laboratory, Richland, Washington

Subsurface concentrations of radon in soil gas are usually several orders of magnitude higher than concentrations in the environment and in buildings. In modeling the transport of radon at the subsurface, it is convenient to specify a zero or small (atmospheric or building) concentration at the subsurface boundary. However, there are conditions where high advective fluxes from the soil and/or stagnant gas regions above the surface might result in potentially significant radon surface concentrations.

A code, Rn3D, was used in one dimension to determine where high pressure gradients in the soil near the surface might reduce the accuracy of radon surface flux estimates and radon soil concentration profiles if a zero concentration were specified at the surface. We also studied the effects on soil concentration profiles and

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surface fluxes of wind speed and surface roughness, using a boundary condition of the following type: surface Rn flux = $k(c-c_o)$. Here, k is a mass transfer coefficient, c is the radon surface concentration, and c_o is the atmospheric radon concentration. One can interpret k^{-1} as a resistance to radon transport across a gas-phase boundary layer. Simulations were performed for several soil moisture levels and five generic soil types: clay, silt, loam, sand, and gravel.

When modeling the entry of radon into a structure, the role of small mass transfer coefficients (<0.01 m/s) near the structure's outside walls could cause local soil radon concentrations to be higher than expected. This possibility is examined using Rn3D in two dimensions.

Calculated subsurface concentrations could be significantly higher near and below the building owing to more stagnant atmospheric conditions near the walls with small k values than those obtained if the stagnant regions are ignored (i.e., using large k values). Using a large mass-transfer coefficient (>0.1 m/s) is nearly synonymous with using the atmospheric concentration boundary condition.

The results of this study are summarized using dimensionless parameters.

AN EXPERIMENTAL TWO-STAGE RAT MODEL OF LUNG CARCINOMA INITIATED BY RADON EXPOSURE

(Thurs., 9:15 a.m.)

J. L. Poncy, P. Laroque, P. Fritsch, G. Monchaux, J. Chameaud, and R. Masse

Commissariat à L'Energie Atomique, Bruyères le Chatel, Fontenay aux Roses, France

We present the results of a two-stage biological model of lung carcinogenesis in rats. Histogenesis of lung tumors was examined,

and DNA content of lung cells was measured by flow cytometry during the evolving neoplastic stage. Tumors were induced in rat lungs after radon inhalation (1600 WLM) followed by a promoter treatment: six intramuscular injections of 5,6-benzoflavone (25 mg/kg of body weight/injection) every 2 weeks. Less than 3 months after the first injection of benzoflavone, squamous cell carcinoma was observed in the lungs of all rats previously exposed to radon. The preneoplastic lesions gradually developed as follows: hyperplastic bronchiolar-type cells migrated to the alveoli from proliferation of bronchioles and alveolar duct cells; initial lesions were observed in almost all respiratory bronchioles. From some hyperplasias, epidermoid metaplasias arose distally, forming nodular epidermoid lesions in alveoli, which progressed to form squamous papillomas and, finally, squamous cell carcinomas. The histogenesis of these experimentally induced epidermoid carcinomas showed the bronchiolo-alveolar origin of the tumor. This factor has to be considered when comparing these with human lesions; in humans, lung epidermoid carcinomas are thought to arise mainly in the first bronchial generations.

DNA cytometric analysis was performed on cell suspensions obtained after enzymatic treatment of paraffin sections of lungs from rats sacrificed during different stages of neoplastic transformations. Data showed the early appearance of a triploid cell population that grew during the evolution of nodular epidermoid lesions to squamous cell carcinomas. The implications of this cell population in neoplastic transformation will be discussed.

DEVELOPMENT OF APPARATUS AND PROCEDURES FOR EVALUATING RADON-RESISTANT CONSTRUCTION MATERIALS *(Wed., First Group, 4:00 p.m.)*

T. D. Pugh,[1] M. B. Greenfield,[1] J. MacKenzie,[1] and R. J. de Meijer[2]

[1]Florida A&M University, Tallahassee, Florida; and [2]Kernfysisch Versneller Instituut, Groningen, The Netherlands

Laboratory facilities and apparatus have been constructed to measure the radon exhalation from, and radon permeability through, various construction materials. This phase of the project has focused on development of the test apparatus and evaluation of the instrumentation. Results indicate significant spatial variability in the radon permeability of polyethylene, even when all test samples were selected from the same roll of material and when no visible differentiation can be made regarding sample quality. Implications for code enforcement are described, and recommendations are offered for refining the equipment and measurement process, setting priorities for future materials testing, and writing specific building code provisions based on the results.

A NATIONAL ORGANIZATION AND STRATEGY FOR MANAGING INDOOR RADON RISKS *(Fri., 8:10 a.m.)*

A. Rannou,[1] S. Bernhard,[2] N. Fourcade,[2] J. F. Pineau,[2] M. C. Robe,[1] and P. Zettwoog[2]

[1]Commissariat à L'Energie Atomique, Fontenay-Aux-Roses, France; and [2]CRPM, Fontenay-Aux-Roses, France

Members of the public should be able to obtain from a national radon-expert organization current information and advice on indoor radon to allow them to decide on necessary corrective measures for their homes. Such an organization should not necessarily be governed by official regulatory policies; rather, it should be an

advisory service. It must, however, avoid promoting specific businesses, and it must not unjustifiably increase public concern about hazards. Also, this organization ought to have broad competence and experience in the radon field.

Management of radon risk requires a complete understanding of the issues and a well-established strategy, ranging from measurements to mitigation measures. Such a strategy includes: screening measurements, long-term integrated measurements, and development of remedial action plans. This strategy should also stress quality assurance in measurement data and the employment of trained personnel.

Trained personnel should be accessible to the public locally. Consequently, it is also the duty of the radon-expert organization to train and assist local specialists, especially in the construction and maintenance of buildings. Finally, the organization must continuously enhance its expertise based on its field experience.

The strategy and perspective of a national organization which is under study in France will be presented and discussed in this paper.

UNATTACHED FRACTION AND SIZE DISTRIBUTION OF AEROSOL-ATTACHED RADON AND THORON DAUGHTERS IN REALISTIC LIVING ATMOSPHERES AND THEIR INFLUENCE ON RADIATION DOSE *(Tues., 1:55 p.m.)*

A. Reineking, G. Butterweck, J. Kesten, and J. Porstendörfer

Isotopenlaboratorium für biologische und medizinische Forschung, Universität Göttingen, Federal Republic of Germany

In all dosimetric models the aerosol particle size and the unattached fractions of radon and thoron daughters are important parameters for estimating the radiation dose to humans. Using various measuring techniques (high-volume impactors, low-pressure cascade

impactors, and screen diffusion batteries) to cover the particle size range from 0.5 nm to 10,000 nm, we measured activity size distributions of radon and thoron progeny in air and the influence of different aerosol sources. We made these measurements under realistic living conditions in a house and in the open air. The unattached fraction f_p was measured with a single-screen technique in conjunction with alpha-spectroscopy.

Activity size distribution measurements of radon and thoron daughters made indoors showed that the mean AMAD of the main activity mode (accumulation mode) of the size distributions of aged aerosols shifted significantly to smaller diameters (AMAD, approximately 200 nm) compared with outdoor aerosols (AMAD, approximately 400 nm). In closed rooms, aerosol sources such as gas heaters or a burning candle added an additional condensation nuclei mode with an AMAD between 10 and 100 nm. Outdoors, resuspension, combustion, and nucleation processes resulted in activity in the nuclei size mode and also in the coarser size ranges (up to a few micrometers).

Our results of indoor and outdoor measurements of the unattached fraction, f_p, of radon potential alpha-energy show that most published calculations of the natural radiation dose received by the public are based on incorrect values. Under normal conditions (low ventilation, without aerosol sources), we found that the mean f_p value, 0.095, was three times higher than that proposed in the literature.

Finally, the dosimetric implications of these experimental data on particle sizes and f_p values on radiation dose are presented.

EXHALATION OF RADON BY MAN* *(Tues., 8:30 p.m.)*

J. Rundo

Argonne National Laboratory, Argonne, Illinois

This paper describes some aspects of the exhalation of radon by man which may be relevant to its internal dosimetry and, therefore, to possible radiobiological consequences. Prolonged exposure of a person to radon results in a reservoir of radon dissolved in body fat and fluids. If the person then moves to an environment with a lower radon concentration, there is a net exhalation of radon, and the initial exhalation rate depends on the radon concentration in the first environment. This is demonstrated for seven persons whose houses contained radon at concentrations varying from 10 Bq m^{-3} to almost 1000 Bq m^{-3}. About 1 h after leaving the house, the subjects' average exhalation rate of radon, expressed as the equivalent volume of house air per unit time, was 236 ml min^{-1}.

In general, the exhalation rate declined in a manner that seems to be predictable from the integral of the equation that describes the retention of a single inhalation exposure to radon. However, the behavior is complicated by a major but short-lived postprandial increase in the exhalation rate of radon by persons whose only source of radon was in the air of their homes. The phenomenon was studied in five subjects, who showed initial exhalation rates ranging from 3 mBq min^{-1} to 200 mBq min^{-1}. The excess radon exhaled amounted to approximately 4 L to approximately 15 L, when expressed as the equivalent volume of house air. This radon must have come from a reservoir in the body; the possible dosimetric and radiobiological consequences of this phenomenon are unknown.

*Work supported by the U.S. Department of Energy, Office of health and Environmental Research, under Contract No. W-31-109-ENG-38.

RECOIL-DEPOSITED ^{210}Po IN RADON DWELLINGS

(Tues., 11:30 a.m.)

C. Samuelsson

University Hospital, Lund, Sweden

Short-lived decay products of ^{222}Rn plate out on all surfaces in a house containing radon gas. Following the subsequent alpha decays of the mother nuclei, the daughter products ^{214}Pb and ^{210}Pb are superficially and permanently absorbed. Vitreous glass is close to ideal as a substratum material. It can be found in all dwellings, and migration of the subsurface activity caused by diffuse transport is thought to be insignificant. Because of its long half-life (22 y), the activity of absorbed ^{210}Pb accumulates in the subsurface. The activity of ^{210}Pb or its decay products can thus reflect the past radon and plate-out history of a house over several decades.

We will present our results and experience from measuring ^{210}Po and ^{222}Rn in about 35 dwellings. In these studies the ^{210}Po subsurface activity of flat glass sheets has been determined nondestructively by alpha spectrometry with a specially developed, windowless pulse ionization chamber. However, it is difficult to evaluate the glass/^{210}Po method as a retrospective method of measuring radon concentrations from field studies alone, as houses with radon levels documented over several decades are very rare.

EPA'S APPROACH TO ASSESSMENT OF RADON RISK *(Thurs., 1:45 p.m.)*

A. Schmidt, J. S. Puskin, N. Nelson, C. B. Nelson

U.S. Environmental Protection Agency, Washington, DC

The Environmental Protection Agency has assessed the potential lung cancer risk to the general population due to radon based on

the Agency's general principles of risk assessment. This same approach has been used to assess the impact on public health of other carcinogenic environmental pollutants. This paper briefly describes the application of EPA's approach to radon and includes a description of the method used by the Agency to estimate that approximately 20,000 lung-cancer deaths per year may be related to radon exposure. Also presented are the weight-of-evidence for classifying radon as a known human carcinogen and the uncertainties associated with estimating risks from radon exposure. These combined factors reflect the extent of the underlying support and the context for EPA's estimates of lung-cancer deaths.

A CASE-CONTROL STUDY OF RADON AND LUNG CANCER IN NEW JERSEY WOMEN *(Thurs., 12:05 p.m.)*

J. B. Schoenberg, J. B. Klotz, and H. B. Wilcox

New Jersey State Department of Health, Trenton, New Jersey

Interviews were previously conducted for 994 women with incident lung cancer and 995 population-based controls. Smoking, occupational, dietary, and residential data were collected. This study was extended to examine the radon/lung cancer association in 433 cases and 402 controls who lived in a single "index" residence for 10+ y from 10 to 30 y prior to diagnosis or selection. Radon concentrations were measured by year-long alpha track detectors in living areas of index residences or were estimated from basement alpha tracks or 4-day charcoal canister measurements obtained in the basements of the residences. Adjusted odds ratios were 1.0, 1.1, 1.3, and 4.2 for concentrations of <37, 37-72, 73-146, and 147-418 Bq m^{-3}, respectively, showing a significant trend ($p = 0.04$). Lung cancer risks showed a weaker trend ($p = 0.09$) with increasing cumulative radon exposure; the relative risk coefficient, 0.00037/Bq m^{-3} equilibrium equivalent radon per annum ([EERa]; 3.4%/working level month [WLM]), was consistent with the range of 0.00005-0.00043/Bq m^{-3} EERa (0.5-4.0%/WLM) generally reported for underground miners. The results of this study must be interpreted

cautiously because of the small numbers of subjects with high radon exposures and because of the possibilities of selection biases. However, the study suggests that findings of radon-related lung cancer in miners can be applied to the residential setting.

Further data collection includes radon measurements from 200 additional houses which were subjects' residences for 4+ y from 5 to 30 y prior to diagnosis or selection; these data will also be included in analyses. This will improve cumulative exposure estimates for 92 substudy subjects and will increase the substudy sample to 483 cases and 442 controls.

DOSE ASSESSMENT OF POPULATION GROUPS EXPOSED TO ELEVATED RADON LEVELS IN RADIOACTIVE ITALIAN SPAS *(Tues., 9:10 a.m.)*

G. Sciocchetti, M. Bovi, G. Cotellessa, S. Tosti, P. O. Baldassini, and E. Soldano

ENEA-CRE, Rome, Italy

The natural spring waters on the Isle of Ischia are among the most radioactive in the world. Therapeutic application of these waters, which contain very high radon concentrations, increases the radon exposures of people treated. People who live and work at radioactive spas may be good subjects for testing to evaluate detectable biological effects, especially because their exposures will be less influenced by synergistic factors than those of underground miners. The aim of our investigation was to characterize radon exposure for population groups exposed to high radon levels.

Our approach takes into account some peculiar requirements of our epidemiological investigations. To obtain representative dose values, workers were classified into groups to obtain statistically significant results suitable for epidemiological pilot studies. Investigations were carried out on the geological aspects of radon sources, environmental parameters, physical and dosimetric factors

which influence radon levels, and related exposures in therapeutic facilities in order to model patterns of radon exposure for the various population groups.

We inventoried hyper-radioactive springs on the island. We identified workers in radon spas who were exposed to increased radiation from inhaled radon daughters and assessed their retrospective radon exposure. Results showed that, under some conditions, spa employees were exposed to elevated levels of radon, which produced up to about 60 mSv y^{-1} equivalent effective dose.

RADON EXPOSURE-MEDIATED CHANGES IN LUNG MACROPHAGE MORPHOLOGY AND FUNCTION, *IN VITRO** *(Wed., Second Group, 9:40 a.m.)*

T. M. Seed, G. K. Niiro, and N. D. Kretz

Argonne National Laboratory, Argonne, Illinois

Bronchopulmonary macrophages play a key role in the normal physiology of respiratory system (e.g., immune surveillance, particle clearance, tissue turnover, etc.). We have explored potential respiratory dysfunctions resulting from radon/radon daughter exposure-related damage of the macrophage lung cell population *in vitro*. In this study, macrophages were isolated from lungs of normal healthy dogs by saline lavage, cultured for varying periods (0 to 120 h) in the presence or absence of radon gas (0 to 3.0 kBq L^{-1}), and assessed for radon dose-dependent changes in cell morphology and function. The *in vitro* culture procedure and the cell-exposure system allowed for detailed alpha particle dosimetry in relation to the assessed biological end points: (1) exposure-dependent changes in macrophage surface topography, and (2) the capacity to elaborate specific hormones (hematopoietins, colony-stimulating factor [CSF]) essential for self-maintenance.

*Work supported by the U.S. Government under contract No. W-31-109-ECG-38.

Highlights of the morphologic assessment indicate that relatively low alpha particle doses (<50 cGy) arising from protracted radon/radon daughter exposure elicited pronounced topographic alterations of the exposed macrophage's cell surface: the normally high surface density of small ridges and microvilli were replaced by the low surface density of large surface ruffles and blebs. Under similar low-dose (<50 cGy) conditions, macrophages were functionally compromised in terms of a suppressed capacity to produce the vital hormone CSF, essential for self-maintenance of the population *in situ*. In contrast, the macrophage's phagocytic capacity appeared unaltered.

AN EXPOSURE SYSTEM TO STUDY THE EFFECTS OF β-CAROTENE ON RADON-INDUCED LUNG PATHOLOGY* *(Wed., Second Group, 3:05 p.m.)*

E. Seifter, P. Goodwin, J. Mendecki, and E. Friedenthal

Albert Einstein College of Medicine, Bronx, New York

Work from our laboratory has established that, in mice, the protective action of supplemental β-carotene provides protection against several insults: gamma-irradiation-induced lymphomas (in C57 strain), cyclophosphamide (a radiomimetic compound)-induced lymphomas, and radiation-induced metastases of existing Lewis tumors.

We now propose long-term studies (20-30 months) on the effects of exposure to radon in these systems. The source is a partially porous earthenware slab (5 x 10 x 2 cm) having a small amount of radium dispersed throughout. Based on its gamma emission, we estimate that it contains 200 μg of radium. In a sealed bell jar, an apparent equilibrium of 100 nCi of radon was reached, a value much

*Work supported by the Renate and Allan B. Hunter Fund.

lower than would be predicted from the radium estimate, leading us to conclude that much of the radon is trapped in the ceramic. In our proposed enclosure the source should produce a radon level of approximately 200 pCi L^{-1}, i.e., 50 to 100 times typical indoor levels in homes in our area. The Environmental Protection Agency recommends that such levels be below 4 pCi L^{-1}, and that levels of 200 pCi L^{-1} (the level calculated to be in our chamber) require immediate action. Thus, the projected radon concentration should be an effective challenge for mice within the chamber but should not produce much radiation dose outside.

DEPOSITION DISTRIBUTION OF UNATTACHED RaA ATOMS IN THE TRACHEOBRONCHIAL REGION *(Tues., 3:40 p.m.)*

M. Shimo[1] and A. Ohashi[2]

[1]Nagoya University, Nagoya, Japan; and [2]Ship Research Institute, Ministry of Transport, Tokyo, Japan

To accurately evaluate a human lung dose, it is important to know the fraction of unattached radon daughters deposited on the surfaces of the trachea and bronchi as well as their exact location. Our experimental results are described for determining the deposition of unattached RaA on a model of the tracheobronchial tree based on Weibel's model of airway dimensions. The airway cast, which simulated generations 0 to 4 of the Weibel model, was placed in a glass cell connected to a chamber filled with radon gas. The radon gas was circulated through the airway model. After radon gas (concentration, approximately 150 kBq m^{-3}) passed through the model at a flow rate of 15 L min^{-1} for approximately 20 min, the model was removed and sectioned in small pieces. Alpha activity on the inner surface of each piece was counted by a small detector with a ZnS(Tl) scintillator. "Hot spots," which had activity several times higher than the surrounding area, were especially observed on the inner side of each generation. The deposition fraction measured

at generation 0 was 2.2 to 2.7 times higher than the value calculated from the Gormley and Kennedy formula; values at other generations agreed with those calculated.

DEVELOPMENTAL TOXICOLOGY OF RADON EXPOSURES* *(Wed., Second Group, 2:20 p.m.)*

M. R. Sikov, F. T. Cross, T. J. Mast, H. E. Palmer, and A. C. James

Pacific Northwest Laboratory, Richland, Washington

Increasing concern about the hazards associated with radon exposure in dwellings may be especially relevant to pregnant women, many of whom spend substantial amounts of time in their homes. There are few data concerning the placental transfer and fetoplacental distribution of inhaled radon and decay products or its effects on the conceptus. One early study found marked fetotoxicity following intravenous or subcutaneous injection of pregnant animals with saline containing dissolved radon, but tissue concentrations and dosimetry were not investigated in that study.

We initiated a study in rats to determine if prenatal effects could be produced by prolonged inhalation exposures to high concentrations of radon throughout gestation. A group of 43 pregnant rats was exposed 18 h d^{-1}, at a rate of 124 working level months (WLM) per day, from 6 to 20 days of gestation (dg), of radon daughters adsorbed onto ore dust. A group of 26 pregnant rats from the same shipment was exposed to a filtered-air atmosphere as controls. At 20 dg, the rats were removed from the chambers and killed. The fetuses were evaluated for the presence of toxic effects, using our standard teratologic protocols. These exposures did not produce detectable reproductive or developmental toxicity, and they were not teratogenic.

*Work supported by the U.S. Department of Energy under Contract DE-AC06-76RLO 1830.

Two of the exposed rats removed from the radon chambers during the last day of exposure were examined for radionuclide distribution and dosimetry. Samples from these rats suggested that the doses to the placenta were roughly threefold those to the fetus. In contrast, we found in previous experiments that another noble gas, krypton, was more uniformly distributed. Radiation doses to the placenta and fetus from radon exposure were less than those to tissues of the pregnant rats. Other dosimetric data related to prenatal exposure will be reported separately at this symposium.

EPIDEMIOLOGICAL IMPLICATIONS OF GEOGRAPHICAL AND TEMPORAL RADON VARIATIONS *(Thurs., 11:40 a.m.)*

D. J. Steck[1] and R. S. Lively[2]

[1]St. John's University, Collegeville, Minnesota; and [2]Minnesota Geological Survey, St. Paul, Minnesota

Epidemiological studies require accurate assessments of total radon-daughter exposures. Short-term radon measurements taken in current dwellings may misrepresent past exposures. In the upper midwest, we have observed significant spatial variation, on a scale of several kilometers, in yearly average indoor radon concentrations. Thus, ecological studies using small samples, or case-control studies using only the current residences for exposure assessment, could misjudge the actual long-term exposures if the size of the geographical cluster used is larger than a county.

Short-term measurements also may introduce unacceptable variation. In a comparison of two measurement techniques in 80 upper-midwest homes, a correlation was found between year-long alpha-track and 2-day charcoal canister measurements. However, the observed coefficient of variation (factor of 2) between measurement protocols may introduce enough scatter to obscure weak correlations in small samples.

A correlation that was observed between lung-cancer rates in 13 rural Minnesota counties and the annual-average radon concentration (median = 100 Bq m^{-3}) estimated from year-long alpha-track measurements was not found when charcoal canister data were used to estimate the radon exposure.

Year-to-year variations may also be important. In 12 homes that have been monitored for longer than 1 y, yearly variations ranged from 0 to 500%, with a median variation of 22%. We are investigating a retrospective detection technique that may improve long-term radon exposure assessments. We have found correlation between the surface alpha activity and radon exposure for glass surfaces exposed from 6 to 2000 kBq y m^{-3}. We have developed an alpha-track detection system that measures both present radon concentrations and exposure history.

SMOKING-PRODUCED MUCUS AND CLEARANCE OF PARTICLES IN THE LUNG *(Tues., 8:50 p.m.)*

T. D. Sterling

Simon Fraser University, Burnaby, British Columbia, Canada

Some studies of miners have shown a lesser relative lung cancer risk for smokers than for nonsmokers. Experiments by Cross and associates in dogs have shown an apparent protective effect of cigarette smoke against radon-daughter and dust exposure. One reason for these results may be the thickened mucous layer in smokers. The continuity of the alveolar fluid film with the tracheobronchial mucous layer allows particle-laden alveoli macrophage to leave the alveoli via the tracheobronchial tree. Alveolar macrophages have, in fact, been found in sputum samples, and the increase in the amount of smoker-produced mucus facilitates this process. The deposition patterns of inhaled particles also appear to depend, in part, on the lung's mucus content. Differences in mucus content can affect deposition patterns between smokers and nonsmokers, leading to different local concentrations of particles in

the lungs. Even when dust particles are deposited relatively uniformly, they tend to migrate toward pleural and bronchial regions. Again, an increase in the amount of smoking-produced mucus would be expected to facilitate this process.

ASSESSMENT OF ECOLOGICAL AND CASE-CONTROL METHODS FOR ESTIMATING LUNG-CANCER RISK DUE TO INDOOR RADON *(Invited paper, Thurs., 4:35 p.m.)*

C. A. Stidley and J. M. Samet*

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The findings of studies of underground miners imply that indoor radon is also an important cause of lung cancer for the general population. Epidemiological studies, including both case-control and ecological approaches, are being used to directly address the risks of indoor radon. Ecological studies conducted to assess the risk of lung cancer due to indoor radon exposure have not consistently shown an association, and case-control studies may be limited by lack of power and bias. Because ecological methods have potentially serious flaws, we examined the use of these methods in the assessment of lung-cancer risk due to indoor radon exposure. We developed a simulation approach that utilizes the Environmental Protection Agency radon survey data to assign exposures to individuals within counties and the risk models recommended by the BEIR IV Committee, NCRP, ICRP, and EPA to project underlying lung-cancer risk. Using the resulting artificial data, we compared risk estimates obtained by ecological regression methods to those obtained from other regression methods and to the true risks

*Presenter

assumed in the data generation. For many of these simulations, the ecological models, while achieving excellent fit to the summary data, gave risk estimates that varied considerably from the true risk. In some scenarios, the risk estimates were negatively correlated with exposure even though the assumed relationship was positive, or they differed from the true risk by several thousand percent. Attempts to improve the ecological models by adding smoking variables, including interaction terms, often yielded worse estimates of risk. Since the situations used in the simulations are realistic, the results from this study indicate that ecological methods may not accurately estimate the lung-cancer risk associated with radon exposure.

DEPOSITION OF "UNATTACHED" RADON DAUGHTERS IN MODELS OF HUMAN NASAL AIRWAYS *(Tues., 7:20 p.m.)*

J. C. Strong[1,2] and D. L. Swift[3]

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In order to estimate accurately an effective dose equivalent for radon daughters, knowledge of their deposition in the lung is required. However, the nose and mouth are effective filters for removing aerosol particles, especially in the range of sizes of "unattached" radon daughters. Therefore, it is equally important to have reliable data on deposition in this region of the respiratory tract.

We will describe our work in studying nasal and oral deposition of "unattached" radon daughters in casts of these airways. Several hollow casts of adult and child nasal and oral airways were fabricated at The Johns Hopkins University from layers of Perspex™ (an acrylic plastic). The shapes of the airway passages were obtained from nuclear magnetic resonance sectional images of healthy

subjects. Radon gas was produced by flushing filtered air through a commercially available ^{226}Ra source and then drawing the gas through a 1.4-L cylindrical tube to allow measurable growth of ^{218}Po activity before passing it through both nasal passages or the oral cavity of a cast. The deposition of "unattached" ^{218}Po was measured by comparing the activity collected on filters mounted in series and in parallel with a cast. Measurements were made at various flow rates (4 to 20 L min^{-1}). The diffusion coefficient (D) of ^{218}Po was measured at each flow rate (Q) by replacing the cast with a stainless steel gauze screen and measuring the activity penetrating the screen. Diffusion coefficients ranged from 0.02 to 0.05 cm^2 s^{-1} and were found to vary as a function of residence time in the ^{218}Po growth tube.

Deposition efficiencies (n) measured with the casts ranged from 50 to 70%, similar to those we found previously using casts of nasal and oral airways from cadavers. However, the data presented here fit the model

$$n = 1\text{-}\exp(-6.9\ Q^{-0.125}\ D^{0.5}),$$

suggested by Cheng, at this conference, for a single-passage nasal cast.

A FACILITY FOR STUDYING THE CARCINOGENIC AND SYNERGISTIC EFFECTS OF RADON DAUGHTERS IN RODENTS *(Wed., Second Group, 3:55 p.m.)*

J. C. Strong and M. Walsh

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Although there is evidence to link lung cancer with radon exposure in miners, studies have not yet adequately demonstrated a link at domestic levels of exposure. Induction of cancer in animals after acute exposure to high levels of radon and radon daughters has been investigated by several laboratories. It is our intention to study the effects of radon and its daughters on rodents following both

acute and chronic exposure. The studies will be extended to investigate the effects of other carcinogens in association with radon daughters.

We will describe a facility in which rodents can be exposed continuously to radon and its daughters for periods of up to several months. The facility consists of two exposure chambers with closed air circuits which are operated independently of each other. Aerosol generators provide controlled vector aerosols onto which radon daughters can attach. Particular attention has been paid to the accurate measurements of the concentrations of radon gas and of individual radon daughters. Techniques have also been developed for measuring the relevant aerosol parameters, namely, "unattached" fraction and activity size distribution of individual daughters and potential alpha energy.

The environment within the facility will be adjusted to be comparable to that found in dwellings with regard to condensation nucleus concentration, "unattached" fraction, equilibrium factor, and activity size distribution. Other vapors and aerosols, such as tobacco smoke, can also be introduced into one of the air circuits to study the combined effects of radiation and toxic chemical agents.

DESIGN, CHARACTERIZATION AND USE OF REPLICATE HUMAN UPPER AIRWAYS FOR RADON DOSIMETRY STUDIES *(Tues., 4:00 p.m.)*

D. L. Swift,[1] Y.-S. Cheng,[2] Y.-F. Su,[2] and H.-C. Yeh[2]

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The size distribution of inhaled radon progeny aerosols is important for accurate dosimetric models. The role of the airways above the trachea is an important determinant of the respiratory distribution of

both attached and unattached progeny aerosols. In order to provide information on the effect of particle size and breathing conditions on the overall and local deposition, we have developed a method to produce a replicate airway model from an *in vivo* magnetic resonance imaging (MRI) coronal scan. The model consists of a sandwich of methylacrylate elements, each element having the thickness of the scan interval. The specific scan is located at the element interface, and the transition is hand-sculpted in the plastic. The adult model thus produced has been characterized both morphologically and fluid mechanically and has a flow resistance typical of normal adults.

The model has several distinct advantages for studies of radon progeny aerosol deposition. After exposure to a radioaerosol (or to an aerosol of an analytically measurable substance) the individual elements can be separated for local deposition determination. The dimensions of specific upper-airway regions can be changed by replacing a small number of elements. The model has been incorporated in an exposure system for determining overall and regional deposition of aerosols whose median diameter is approximately 1.7 nm. Measurements at several flow rates are presented to demonstrate use of the model in radon dosimetry. The model should also be useful for determining the airway deposition of other environmental aerosols.

SOIL-GAS AND INDOOR RADON DISTRIBUTION RELATED TO GEOLOGY IN FREDERICK COUNTY, MARYLAND *(Poster, Wed., First Group, 1:15 p.m.)*

S. L. Szarzi, G. M. Reimer, and J. M. Been

U.S. Geologic Survey, Denver, Colorado

The two major physiographic provinces that occur in Frederick County, Maryland, are the Piedmont and the Blue Ridge. Soil-gas measurements were taken for a study designed to show the

relationship between geology and soil-gas radon concentrations. The local geology causes varied soil-gas concentrations that contribute to radon availability for indoor accumulations. The western part of the county, where quartzites form the core of ridge and mountains, has a mean soil-gas radon concentration of 26 kBq m^{-3} (700 pCi/L). The eastern part of the county, containing the phyllites of the Piedmont Province, has a mean soil-gas concentration of 59 kBq m^{-3} (1600 pCi/L). In the southeast portion of the county, where soil-gas radon concentrations exceeded 75 kBq m^{-3} (2000 pCi/L), the average indoor radon concentration (from charcoal canister measurement) was 1.9 kBq m^{-3} (50 pCi L^{-1}). This observation supports previous work showing that the soil-gas radon concentration is a primary component in determining the coupling characteristics of radon transport between soils and homes. Data acquired by studies such as these throughout the United States are essential to identify regional radon "hot spots" which may produce elevated indoor radon levels of unquestioned risk.

PRENEOPLASTIC TRANSFORMATION OF RAT TRACHEAL EPITHELIAL CELLS BY INHALED RADON PROGENY* *(Wed., Second Group, 1:05 p.m.)*

D. G. Thomassen, G. J. Newton, and R. A. Guilmette

Inhalation Toxicology Research Institute, Albuquerque, New Mexico

Because all individuals are exposed to alpha radiation from inhaled radon progeny, we conducted research to address a basic question concerning the role of inhaled radon progeny in respiratory carcinogenesis: Does inhalation of radon progeny induce the early, preneoplastic changes involved in respiratory carcinogenesis? The rat tracheal cell was our model for experimental carcinogenesis.

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Rats were given exposures of approximately 900 working level months (WLM) of radon progeny over 3 to 4 h. Cigarette smoke, similar to that associated with sidestream smoke, was used as a vector aerosol. Following exposure, tracheal cells were isolated and examined in culture for preneoplastic variants. The frequency of preneoplastic variants was threefold greater in cell populations isolated from animals exposed to radon progeny compared to that in controls exposed only to smoke.

The persistence of radon-progeny-induced damage was also determined. The fraction of cells isolated from exposed animals that was able to form colonies increased with time after exposure, reflecting repair or, more likely, cell turnover. Similarly, with increasing time after exposure, the frequency of preneoplastic variants in the tracheal cell population was lower than the frequency observed in cells isolated from tracheas immediately after exposure.

These results demonstrate that (1) respiratory cells exposed *in vivo* sustained biologically damaging doses of radiation from inhaled radon progeny, (2) inhaled radon progeny induced preneoplastic changes in respiratory cells, and (3) radon-progeny-transformed cells were repaired, or lost *in vivo* with time after exposure. This model of respiratory carcinogenesis is useful for characterizing the role of inhaled radon progeny in respiratory carcinogenesis and for defining the risk from exposure.

DEPOSITION OF RADON PROGENY IN NONHUMAN PRIMATE NASAL AIRWAYS* *(Tues., 7:45 p.m.)*

H. C. Yeh, Y. S. Cheng, Y. F. Su, and K. T. Morgan

Lovelace Biomedical and Environmental Research Institute, Albuquerque, New Mexico

Radon progeny, usually associated with ultrafine particles, range in diameter from 1 to 5 nm for the "unattached" fraction and from 5 to 200 nm for those attached to indoor aerosols. To assess the health effects of inhaling radon progeny indoors, it is necessary to study the regional deposition of these inhaled ultrafine particles. Laboratory animals are often used in studies of the toxicity of inhaled particles and vapors. Information on deposition of particles larger than 0.2 μm in the nasal passages of laboratory animals is available; however, there is little information on the deposition of ultrafine particles (less than 0.2 μm). In this report, we describe the use of nasal casts of rhesus monkeys to measure total deposition of ultrafine aerosols, including unattached ^{220}Rn progeny, in a unidirectional flow system. From these casts we obtained deposition data for monodisperse silver or sodium chloride aerosols, with particle sizes ranging from 0.2 to 0.005 μm. We included several inspiratory and expiratory flow rates that represented normal breathing and both under- and over-ventilation. The deposition of ^{220}Rn progeny in the size range between 1 to 3 nm was also studied. The deposition efficiency was larger for the smaller particle size and decreased with increasing particle size and flow rate, indicating that diffusion was the dominant deposition mechanism. Based on assumptions of turbulent flow and complete mixing of aerosols in the nasal airways, a general equation in the form,

$$E = 1\text{-}\exp(-a\, D^b Q^c) \quad \text{for } d_p < 0.2\ \mu\text{m},$$

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was obtained, where E is the deposition efficiency, d_p the particle diameter, D the diffusion coefficient, and Q the flow rate. Constants a, b, and c are estimated from experimental data, for either inspiration or expiration. These mathematical expressions will be useful in the future for making modifications of both deposition and dosimetry models.

ON THE NANODOSIMETRY OF RADON ALPHA PARTICLES* *(Tues., 9:30 p.m.)*

M. Zaider

Center for Radiological Research of Columbia University, New York, New York

A currently accepted tenet is that energy deposition at the nanometer level (rather than conventional microdosimetry) determines the biological effects of ionizing radiation. Many previously established experimental techniques (e.g., the Rossi proportional counter) or theoretical methods (e.g., simplified calculations using the continuous slowing-down approximation [CSDA] are inapplicable to the study of nanodosimetry). The peculiarities of the geometry of exposure to radon progeny further complicate the problem because the conditions under which several "classical" models of radiation action are obtained (e.g., the α-ß formulation of the Theory of Dual Radiation Action, which is built on microdosimetry) are no longer valid. It thus becomes clear that not only new techniques but new concepts are required to describe the effects of radon alpha particles.

In this paper we discuss a number of computational aspects specific to radon nanodosimetry. In particular, we describe the novel concept of "associated surface" (AS), necessary for efficiently

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converting Monte-Carlo-generated particle tracks to nanodosimetric spectra. The AS is the analog of Lea's associated volume, applied to radiation sources subject to the geometrical restrictions of internal exposure.

We systematically analyze factors affecting the nanodosimetry of radon progeny, such as the distance between the radioactive source and the sensitive volume, the size of the sensitive volume, and CSDA versus full Monte-Carlo track generation.

MODELING THE INTERACTION BETWEEN RADON AND TOBACCO SMOKE: A BIOLOGICALLY BASED APPROACH *(Thurs., 10:05 a.m.)*

J. M. Zielinski and D. Krewski

Health and Welfare Canada, Ottawa, Ontario, Canada

In this paper, the effects of joint exposure to two carcinogens are explored within the context of the two-stage clonal expansion model of carcinogenesis. This biologically based model provides a useful framework for the quantitative description of carcinogenesis and for defining carcinogenic agents that act as initiators, promoters, and completers.

This model is applied to epidemiological data on human exposure to radon and tobacco and is used to evaluate the interaction between those two risk factors for lung cancer. In particular, we examine typical exposure patterns involving continuous lifetime exposure to radon coupled with partial lifetime exposure to tobacco smoke. The age-specific risks for lung cancer are then interpreted in relation to the additive and multiplicative models of relative risk.

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